

LRS@LHC

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Based on: H. D., G. Perez, and A. Soni

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Introduction

- SM with a Higgs: quadratic sensitivity to Λ_{UV} .
 - EW precision: $\Lambda_{UV} \gtrsim 10$ TeV; “little hierarchy”.
 - Flavor data: $\Lambda_{UV} \gtrsim 10^3$ TeV; “flavor-weak hierarchy”.
 - Gravity: $\Lambda_{UV} \sim M_P \sim 10^{19}$ GeV; “Planck-weak” hierarchy.
- Randall-Sundrum (RS) model (1999): Planck-weak hierarchy.
 - Distinct signatures: spin-2, . . . TeV-scale resonances.
- SM in 5D bulk, fermion profiles → model of flavor.
 - Precision constraints → multi-TeV resonances, more structure needed.
 - Realistic 4D flavor → RS signatures more elusive.

Suppressed coupling of light SM fermions to the KK states.

- Consider RS as a model of *flavor*.
- $\Lambda_{UV} \sim M_5 \sim 10^3$ TeV: truncated bulk (conformal window).

Little Randall-Sundrum (LRS) model.

- Separate Yukawa dynamics:

A number of precision constraints relaxed.

LRS always less constrained than RS counterpart.

- Important consequence of truncation:

Enhanced light fermion, e.g. di-lepton, signals for KK modes.

⇒ Significantly improved discovery prospects.

Short Review of the RS Model

$$ds^2 = e^{-2\sigma} \eta_{\mu\nu} dx^\mu dx^\nu - r_c^2 d\phi^2,$$

$$\sigma = kr_c |\phi|$$

$k \sim M_5 \sim M_P$: 5D curvature scale

r_c : radius of compactification, $\phi \in [0, \pi]$.

The UV (Planck) brane $\phi = 0$.

IR (TeV) brane $\phi = \pi$.

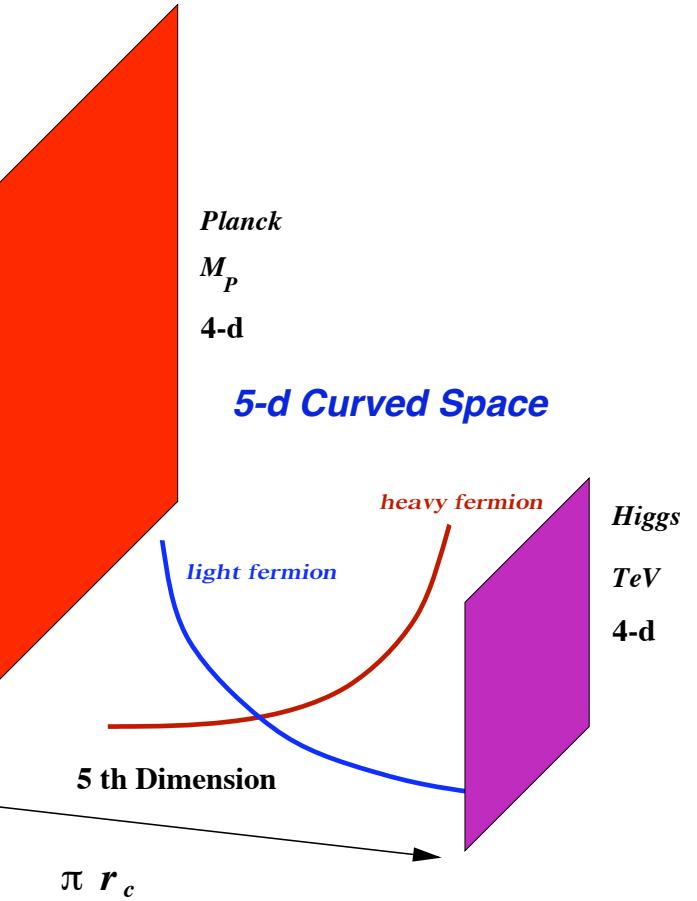
$$\kappa \equiv k e^{-kr_c\pi} \sim \text{TeV}$$

$$\Rightarrow kr_c \simeq 11$$

Bulk fermion masses, $m_i = c_i/k$.

Light zero-mode fermions UV-localized for $c_i \sim 1$:

- Realistic small masses.
- High effective cutoff for dangerous operators.



However, there is still more to worry about. . . .

Suppressed KK signals

Oblique Corrections

$$S_{tree} \approx 2\pi (v/\kappa)^2 \quad ; \quad T_{tree} \approx \frac{\pi}{2\cos\theta_W^2} (v/\kappa)^2 \underbrace{(kr_c\pi)}_{\approx 35}$$

- $\kappa \equiv ke^{-kr_c\pi} \sim m_{KK}^{\text{gauge}}/2.5$
- T_{tree} : KK-tower mixing via EWSB $\propto kr_c\pi$
- $m_{KK}^{\text{gauge}} \sim 3 \text{ TeV} \rightarrow T_{tree} \sim 3$ (RS)
- Data: $|S| \sim |T| \sim 0.1 - 0.3$.

Little Randall-Sundrum (LRS) Model:

- Truncated; $kr_c\pi = 6$ ($M_5 \sim 10^3$ TeV).
- LRS truncation factor: $y \equiv (kr_c\pi|_{RS})/(kr_c\pi|_{LRS}) \approx 6$.
- Flavor same as RS: λ_5 (5D Yukawa) and fermion IR-profiles.
- Suppression of T_{tree} in LRS.

$$m_{KK}^{\text{gauge}} \sim 3 \text{ TeV} \rightarrow T_{tree} \sim 3/y$$

- S_{tree} : Largely *universal* shift in light fermion-gauge coupling.
 - (i) zero-mode-KK mixing $\sim \sqrt{kr_c\pi}$.
 - (ii) Fermion coupling to KK modes $\sim 1/\sqrt{kr_c\pi}$.

$\Rightarrow S_{tree}$ unchanged after LRS truncation.

- δT : UV-sensitive loops, cutoff operators: $m_{KK} \gtrsim 10$ TeV.
 - LRS: δT loop and cutoff contributions same as RS.

Need gauged 5D custodial symmetry:

$$SU(2)_L \times SU(2)_R \times U(1)_X.$$

- T : Eliminate tree, cutoff, UV-sensitive loops.
- $S, T \Rightarrow m_{KK} \gtrsim 3$ TeV. [Agashe, Delgado, May, Sundrum, 2003](#)
- Same for RS and LRS.

Non-Oblique Corrections & Flavor Physics

$Z\bar{b}b$ data: $\delta g \lesssim 0.3\%$

RS: $m_{KK}^{RS} \gtrsim 3$ TeV with custodial symmetry and \mathbb{Z}_2 .

Otherwise: $m_{KK}^{RS} \gtrsim 5$ TeV. Agashe, Contino, Da Rold, Pomarol, 2006

LRS:

(A) EWSB KK-tower mixing: $\delta g \propto (kr_c\pi/m_{KK}^2)f_{Q^3}^2$.

$f_{Q^3}^2$ unchanged: $\sqrt{y} \approx 2.4 \Rightarrow m_{KK}^{LRS} \gtrsim 2$ TeV.

(B) $b_L - b_{KK}$ mixing:

- $b_R'^{KK}$: Absent for a $L-R$ singlet t_R or no custodial symmetry.
- b_R^{KK} mixing: $\delta g \sim 4[(v/\sqrt{2})\lambda_5 k f_{Q^3}/m_{KK}(b_R)]^2$.

$m_{KK}(b_R) \gtrsim 4$ TeV $\Rightarrow m_{KK}(\text{gauge}) \gtrsim 3$ TeV in LRS (no \mathbb{Z}_2)!

$$\Delta F = 2$$

- Tree-level KK gluon exchange contribution to ϵ_K .

$h^{\text{RS/SM}} \lesssim 0.3$, $(V - A) \times (V - A) \Rightarrow m_{KK} \gtrsim 3 \text{ TeV}$ (RS).

Agashe, Perez, Soni, 2004

- Dominant contribution from $(V - A) \times (V + A)$:

Beall, Bander, Soni, 1981

$\mathcal{O}(10)$ suppression, $\mathcal{O}(100)$ chiral and relative RGE enhancements.

$m_{KK} \gtrsim 20 \text{ TeV}$ (RS) with $\mathcal{O}(30\%)$ uncertainty.

UTfit Collaboration, 2007

Csaki, Falkowski, Weiler, 2008

$h^{\text{RS/SM}} \propto kr_c \pi / m_{KK}^2$, flavor (f_x) unchanged:

LRS bounds smaller by $1/\sqrt{y} \approx 1/2.5$.

LRS Phenomenology and Golden Modes

- $g_{KK}|_{UV} \sim g_4/\sqrt{kr_c\pi}, \quad g_{KK}|_{IR} \sim g_4\sqrt{kr_c\pi}.$
- (i) Broad KK states become narrower by y .
- (ii) Width into light states (e^+e^- , $u\bar{u}$, ...) enhanced by $y \rightarrow \text{BR} \sim y^2$.
- (iii) $\sigma(f_i\bar{f}_j \rightarrow KK \rightarrow f_k\bar{f}_l) \propto \Gamma(KK \rightarrow f_i\bar{f}_j) \text{BR}(KK \rightarrow f_k\bar{f}_l)$
- (i) \oplus (ii) \oplus (iii) $\Rightarrow \mathcal{S} \sim y^3$ and $\mathcal{B} \sim 1/y$ (over the width); $\mathcal{S}/\mathcal{B} \sim y^4$.

LRS, $y \approx 6 \Rightarrow \mathcal{S} \rightarrow \mathcal{O}(100)\mathcal{S}$; $\mathcal{S}/\mathcal{B} \rightarrow \mathcal{O}(1000)\mathcal{S}/\mathcal{B}$!

$M_{Z'} \sim 4 \text{ TeV}$ and $L = 100 \text{ fb}^{-1}$: $Z' \rightarrow \ell^+\ell^-$, $\ell = e, \mu$.

Compare with RS: $M_{Z'} \sim 2 \text{ TeV}$ and $L = 1000 \text{ fb}^{-1}$. Agashe *et al.*, 2007

Revived prospects for golden modes!

LRS Tests:

- Compare BR's of Z' into $W_L W_L, Z_L h, t\bar{t}$ versus into light fermions.
 - Distinct LRS signature.
- Enhanced LRS discovery potential for elusive SM KK fermions.
- LRS scaling: λ_5 mediated processes relatively stronger.
- Graviton KK production:

Gluon fusion cross section $\propto [(k/M_5)/kr_c\pi]^2 (k/M_5)(x_G/m_G)^2$.
Generic LRS: $k/M_5, kr_c\pi$ shrink by $\mathcal{O}(y)$.

\therefore LRS KK graviton discovery unlikely at LHC (more than RS case).

Holography

- $1/g_4^2 = \tau_{\text{UV}} + \tau_{\text{IR}} + \underbrace{\log(k/\kappa)}_{kr_c\pi}/(kg_5^2)$ $\tau_{\text{UV},\text{IR}}$ small QM corrections
- Dual large N CFT: $kg_5^2 \sim 16\pi^2/N$.
LRS dual to larger N CFT : $N^{\text{LRS}} \sim yN^{\text{RS}}$.
- $N \rightarrow \infty$: inter-composite (Higgs-CFT) interactions weaker.
 $\therefore T_{tree}$ smaller.
- S_{tree} : mainly universal vertex correction, unchanged.
[Mixing] \times [light fermion coupling]: $\sim 1/\sqrt{N} \times \sqrt{N}$.
- LRS: λ_5 unchanged \rightarrow separate “Flavor CFT”: $N_F \sim N^{\text{RS}} < N^{\text{LRS}}$.

Non-universality from compositeness held fixed.

ρ - γ Mixing & LHC Signals

- ρ - γ mixing $\propto \sqrt{N}$
 - Composite (KK) width into light fermions $\Gamma_f \propto N$
- Inter-composite decoupling as $N \rightarrow \infty$.
 - Total width $\Gamma_T \propto 1/N$.

Dominated by composite (H, t, \dots) channels.

- $\sigma(f_i \bar{f}_j \rightarrow KK \rightarrow f_k \bar{f}_l) \propto \Gamma(KK \rightarrow f_i \bar{f}_j) \text{BR}(KK \rightarrow f_k \bar{f}_l)$

$q\bar{q} \rightarrow Z' \rightarrow e^+e^-, \mu^+\mu^-, \dots \Rightarrow \mathcal{S} \sim N^3$ and $\mathcal{B} \sim 1/N$, over Γ_T .

Significantly improved LHC reach for LRS, since $y = N^{LRS}/N^{RS} \gg 1$.

Truncation & IR Probes of UV

- Golden modes (di-lepton channels) sensitive to y :

$$\mathcal{S} \sim y^3.$$

- LRS, $y \approx 6$: TeV $\rightarrow 10^3$ TeV; $\mathcal{S}_{LRS} \sim 200\mathcal{S}_{RS}$.
- Other truncations are possible:
 - TeV $\rightarrow 10^{10}$ GeV (ν_R mass, . . .): $y \approx 2$; $\mathcal{S} \sim 10\mathcal{S}_{RS}$.
 - TeV $\rightarrow 10^{15}$ GeV (GUT): $y \approx 1.3$; $\mathcal{S} \sim 2\mathcal{S}_{RS}$.

Measuring TeV-scale widths and BR's yields UV information:

Size of 5D slice/conformal window.

UV-Completion

- The Planck-weak hierarchy: UV-completion of LRS.
- $M_5 \sim 10^3$ TeV too low to address \mathcal{B} and \mathcal{L} .
 - More model building, UV physics.
 - $n - \bar{n}$ oscillations acceptable, may be accessible in near future.
- Recent LRS UV-model: K. McDonald arXiv:0804.0654 [hep-th].
 - 6D geometry, 2 warped directions.
 - LRS a 5D slice (4-brane), with $M_5 \sim 10^3$ TeV \rightarrow TeV.
 - Warping along the 6th dimension: $M_6 \sim M_P \rightarrow 10^3$ TeV.
 - Generalized to n -warped spacetime.

Summary & Conclusions

- LRS: predictive warped model of flavor, cutoff at $\mathcal{O}(10^3)$ TeV.
- Separate gauge and flavor dynamics.
- Many contributions to precision data suppressed.
- Return of the golden modes (e.g. di-leptons)!
 - LHC discovery prospects much better than the RS counterpart.
- Dual CFT: larger N dynamics for the weakly gauged sector.
- Collider physics very sensitive to truncation.
 - TeV data → UV-scale/conformal window.
- UV-completion: stabilize $\Lambda_{UV}^{LRS} \sim 10^3$ TeV (hierarchy).